

The Effect of Fill Volume on Heat Transfer From Air-Cooled Thermosyphons

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The effect of fill volume on the heat transfer performance of a cylindrical thermosyphon with an aspect ratio (ratio of the length of the evaporator section to the inner diameter) of 2.33 immersed in a cooling air flow is investigated. The fill volume was systematically varied from 0% to 70.3% of the volume of the evaporator section in a copper-water thermosyphon having an inner diameter of 19 mm. The condenser section was immersed in a uniform air flow in the test section of an open return wind tunnel. The heat transfer rate was measured as a function of evaporator temperature and fill volume, and these results were characterized by three distinct regions. From 0% to roughly 16% fill volume (Region I), the low rate of heat transfer, which is insensitive to fill volume, suggests that dry out may be occurring. In Region II (extending to approximately 58% fill volume), the heat transfer rate increases approximately linearly with fill volume, and increasing evaporator temperature results in decreased rate of heat transfer. Finally, in Region III (from roughly 58–70.3%), the rate of heat transfer increases more rapidly, though still linearly, with fill volume, and increasing evaporator temperature results in increased rate of heat transfer. The thermosyphon rate of heat transfer is greatest at 70.3% fill volume for every evaporator temperature. [DOI: 10.1115/1.4023039]

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1 Introduction

A closed two-phase thermosyphon is an evacuated, closed vessel containing some amount of a working fluid that is used as a heat transfer device where the primary transport method is through the phase change of the working fluid. As they are both simple and highly effective, thermosyphons offer a potential solution to a number of passive thermal management problems encountered in engineering applications. While most thermosyphons have evaporator and condenser sections of comparable length, the present investigation examines a configuration with many practical applications for thermal management problems: a short evaporator section with a much longer condenser section that is immersed in a cooling airflow. This study examines the case of a cylindrical copper-water thermosyphon and investigates the effect of fill volume on the heat transfer performance, i.e., rate of heat transfer.

Over the past several decades, there have been a number of studies that have addressed the question of the effect of fill volume on thermosyphon performance, typically for very long and thin thermosyphons that apply a cooling jacket at the condenser section [1–5]. While a number of studies have examined the effect of fill volume on thermosyphon heat transfer, few of them have examined the case of thermosyphons with both a short evaporator section and an air-cooled condenser, which is a practical configuration for many thermal management problems [6,7].

The experimental setup used to test the heat transfer rate of a low aspect ratio thermosyphon is described as follows. The thermosyphon test sample was positioned in a wind tunnel with the condenser immersed in the cooling air flow of the test section and with the evaporator placed in an insulated heater block, which was heated by electrical cartridge heaters. At steady-state conditions, the power supplied to the heaters is equivalent to the energy transfer to the air stream (minus the rate of heat transfer from the heater block to its surroundings). For ease of measurement, the thermosyphon's rate of heat transfer to the air stream is determined by measuring the power supplied to the heaters, as shown in Fig. 1. The thermosyphon's rate of heat transfer to the airstream was measured as a function of the evaporator temperature and fill volume.

This study was intended to serve as an extension of De Cecchis' [7] work, which had an identical experimental setup, where the effect of fill volume on thermosyphon heat transfer performance was investigated for cases where the evaporator section is

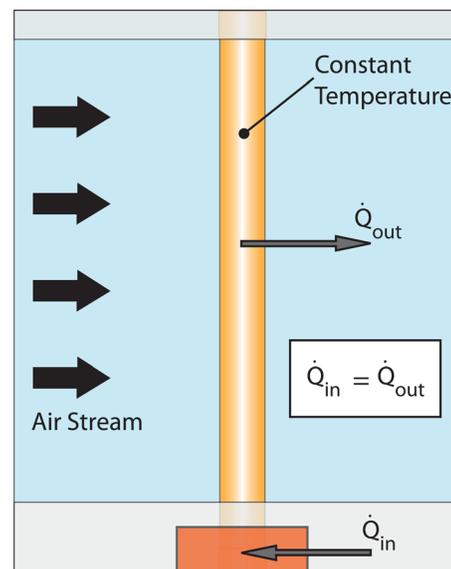


Fig. 1 An illustration of the steady state nature of the experiment where the rate of heat transfer to the airstream, \dot{Q}_{out} , is equivalent to the power input to the electrical cartridge heaters, \dot{Q}_{in}

overfilled. The fill volume in this work was measured as a percentage of total cavity volume, and the current study departed from that in order to more easily compare to the existing literature. Fill volumes ranging from 70.3% to 297.3% of the volume of the evaporator section (10–40% of the total cavity volume) were examined and it was found that the output heat transfer rate was insensitive to fill volume in this range. This is thought to be due to pool boiling as a result of the overfilled evaporator section. These previous experimental results prompted the current investigation of fill volumes smaller than the volume of the evaporator section.

2 Experimental Details

The thermosyphon was constructed from copper pipe (General Purpose Alloy 122) with de-ionized water used as the working fluid. The thermosyphon measured 330 mm long with 13 mm end caps welded to each end of the pipe. Electron beam welding was chosen over standard or silver soldering for end cap attachment due to its minimization of the introduction of foreign material and the resulting strong, solid weld that would stand up to high pressures during operational use. Upon completion of the welding process and assembly, the thermosyphon was hydrostatically pressure-tested to 689 kPa (100 psia). Detailed dimensions of the thermosyphon are given in Table 1. This thermosyphon has an aspect ratio, defined by Noie [1] as the ratio of the length of the evaporator section to the inner diameter, of 2.33. A visual schematic of the thermosyphon is displayed in Fig. 2.

In order to examine the effect of fill volume on heat transfer rate, a reservoir was designed and constructed to allow for the fill volume to be changed between experiments. The end cap nearest the condenser section was fitted with two tubes: the first connecting to a pressure transducer and the second connecting to both a vacuum pump for evacuating the thermosyphon cavity and the fluid reservoir to enable the adjustment of the fill volume without compromising the vacuum in the cavity. The vacuum pump, a Pfeiffer TSH-064D pumping station with an IKR-251 cold cathode gauge, was calibrated at the factory to pump down to a vacuum of 10^{-7} mbar. The completed thermosyphon-fluid reservoir system was attached to the vacuum pump and the thermosyphon was evacuated. After evacuation, the tubing connecting to the vacuum pump was cold-welded. This experimental setup is displayed in Fig. 3.

A copper block was used as the heat source for the evaporator section and was drilled with two 6.35 mm holes to allow for the insertion of two 200 W electrical cartridge heaters (not shown in Fig. 1). The block itself was insulated to minimize heat transfer to the surroundings. The surface of the thermosyphon to be inserted into the heater block was coated with a thin layer of OMEGA-THERM 201 high temperature high thermal conductivity paste, which served as an interface between the heater block and the thermosyphon. The thermosyphon was not removed from the heater block during experiments.

The surface temperature along the condenser section was measured using K-type self-adhesive thermocouples applied at locations 25.4 mm, 76.2 mm, 127.0 mm, 177.8 mm, and 228.6 mm above the bottom of the condenser section of the thermosyphon. The location of these thermocouples is illustrated in Fig. 2. The thermocouples were wired to an Omega TEMPSCAN/1100 temperature scanner with an OMB-TEMPTC-32B board installed.

Table 1 Thermosyphon characteristics

Characteristic	Value
Inner diameter	19.05 mm
Aspect ratio	2.33
Internal volume	94 ml
Evaporator length	44.5 mm
Adiabatic length	19.5 mm
Condenser length	266 mm

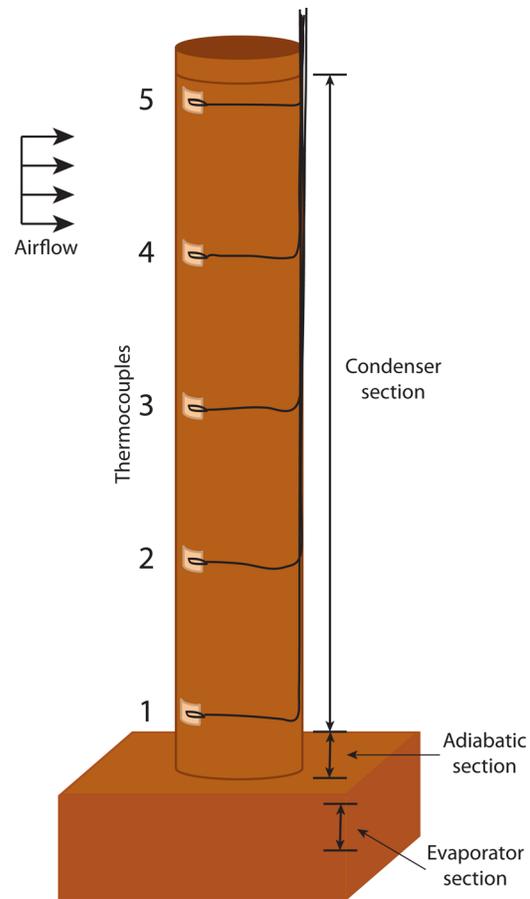


Fig. 2 An illustration of the thermosyphon and heater block used in these experiments, including the locations of the five thermocouples placed along the length of the condenser section (spaced equally apart at distance of 50.8 mm)

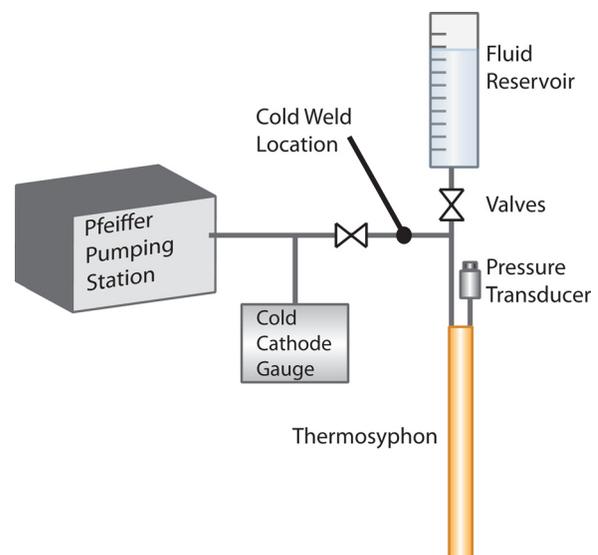


Fig. 3 A diagram illustrating the configuration of the vacuum system, fluid reservoir, and the thermosyphon

Data acquisition was controlled with Omega Chartview installed on a desktop computer.

The temperature of the heater block was also measured using the same type of thermocouple, which was attached to the top of the block. This temperature was assumed to be equivalent to the

evaporator temperature due to the small size of the block and the high thermal conductivity of the copper. To confirm this assumption, the evaporator temperature was calculated using the standard expression for cylindrically symmetric steady state conduction from the cartridge heaters to the evaporator section as outlined in heat and mass transfer textbooks [8]. The inputs for this calculation were the heater block temperature, the input rate of heat transfer, and the thermal conductivity of both the copper and the high thermal conductivity paste. In every case, the approximation of the evaporator temperature was within the error of the heater block temperature measurement.

The ac power input to the cartridge heaters was measured with a Power Monitors Inc., Eagle 120, which is a residential/commercial receptacle recorder. The recorder was connected to the data acquisition computer via a USB port and controlled using PROVISION software. Prior to experiments, the rate of heat transfer from the heater block itself to the surroundings through layers of insulation was measured at each evaporator temperature. This was defined as an offset, which was subtracted from the measured power supplied to the heaters for each experiment. After steady state operation is achieved, temperature and power input data are taken at a sampling rate of one Hertz over a ten minute period and averaged over that time.

3 Experimental Results

The power supplied to the heaters (equivalent to the sum of the output heat transfer rate and the heat transfer rate from the insulated block to the atmosphere), thermosyphon surface temperature, and internal pressure were measured for several fill volumes ranging from 0% to 70.3% in increments of 4.7%. These fill volumes were measured at room temperature prior to the beginning of the experiment. The maximum fill volume of 70.3% was chosen to match De Cecchis' [7] smallest fill volume of 10%, expressed as a percentage of total cavity volume.

At each fill volume, the power supplied to the heaters, surface and heater block temperatures, and internal pressure were measured at the following evaporator temperatures (heater block

temperatures): 121 °C, 135 °C, 149 °C, and 163 °C. During testing, the airflow speed in the wind tunnel section was set to 44.7 m/s (100 mph) and the ambient temperature remained at a fairly constant 23 °C. Figure 4 presents the rate of heat transfer to the airstream as a function of fill volume for the four evaporator temperatures investigated. The repeatability error associated with the reported fill volumes is approximately $\pm 1.6\%$, and the total error (including repeatability and propagation of error) associated with the reported heat transfer rates is approximately ± 5 W.

There are three clearly defined regions of differing behavior in Fig. 4. The first, Region I, ranges from 0% to roughly 16% fill volume. Region II extends up to roughly 58% fill volume, and Region III covers the final range up to 70.3%. In Region I, the rate of heat transfer is independent of fill volume for all evaporator temperatures. This lack of sensitivity to fill volume is possibly due to dry out occurring given the small amount of working fluid present. The rate of heat transfer increases approximately linearly with fill volume in Region II. In this range, lower evaporator temperatures generally correspond to higher rates of heat transfer. Despite the general trend, there is an anomaly in the data obtained for 121 °C evaporator temperature; there is a spike in rate of heat transfer at the lower end of Region II (between 20% and 30% fill volume). As the data used to monitor the performance (internal pressure and surface temperature) did not indicate any unusual behavior in this region, it is not clear why the rate of heat transfer in this region is elevated. The rate of heat transfer also linearly increases with fill volume in Region III, but the higher evaporator temperatures now correspond to higher rates of heat transfer. One noteworthy feature of Region III is that the rate of heat transfer slope experiences a significant increase for the 149 °C and 163 °C evaporator temperatures, whereas the slopes for the 121 °C and 135 °C evaporator temperatures remain approximately the same as they are in Region II.

The surface temperature measurements along the condenser section were collected in part to serve to corroborate the heat transfer rate measured during the experiments. An estimated heat transfer rate from the condenser section to the cooling airflow was obtained by first calculating the convection heat transfer coefficient using the Zhukauskas correlation for flow over a circular

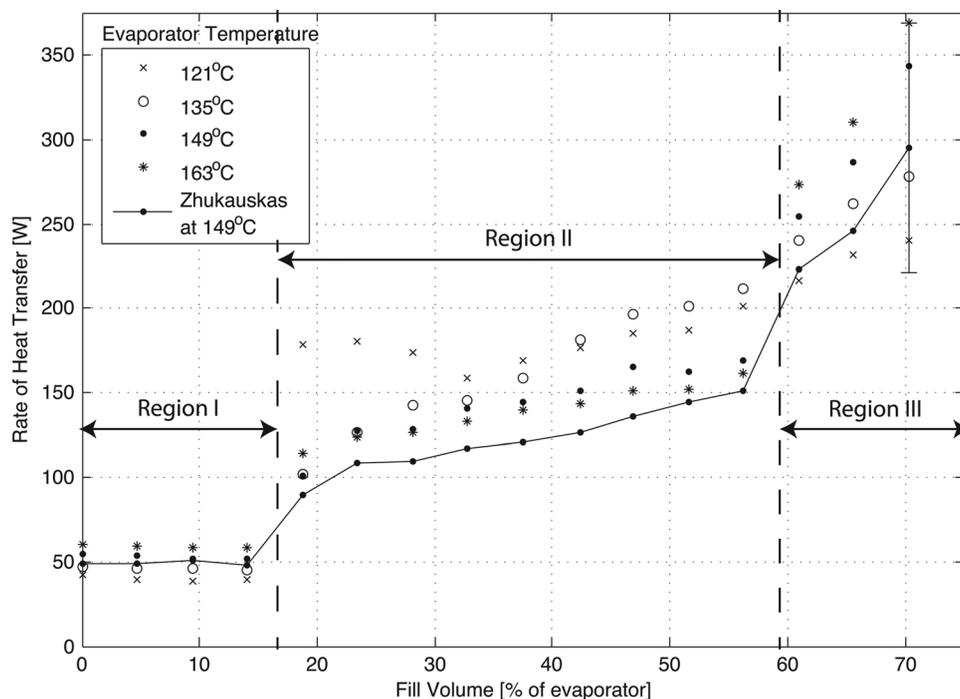


Fig. 4 The rate of heat transfer for four evaporator temperatures at various fill volumes and the predicted rate of heat transfer for the 149 °C evaporator temperature (an example error bar for the Zhukauskas correlation is provided at 70.3% fill volume for the 149 °C evaporator temperature)

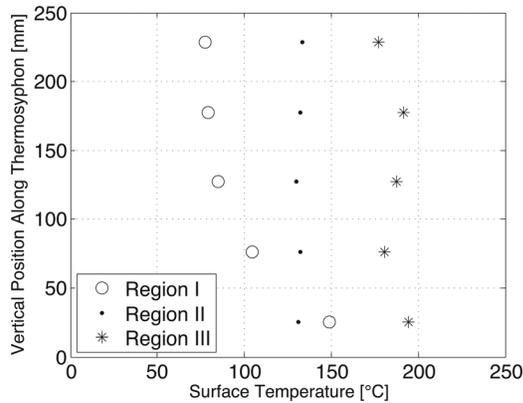


Fig. 5 The surface temperature distribution along the length of the thermosyphon for selected fill volumes in each region at the 149 °C evaporator temperature

cylinder as given in textbooks [8]. The inputs to this correlation included the Reynolds number (6.6×10^4 on average) and temperature of the airflow (23 °C on average) and the averaged temperature along the condenser section. After obtaining the convection heat transfer coefficient, the convective heat transfer rate was calculated. The calculated heat transfer rate using the Zhukauskas correlation at the 149 °C evaporator temperature is plotted along with the measured heat transfer rates in Fig. 4. While not shown, similar results were obtained at the other evaporator temperatures. It is mentioned in Incropera that this correlation, along with others, are only accurate to within 25% of the value at best. The error associated with these calculated values is shown only for the 70.3% fill volume for clarity of the plot, but every measured data point falls within 25% of the corresponding calculated value for all evaporator temperatures and fill volumes. Despite the fact that the predicted output heat transfer rate values fall within the error associated with the correlation, the predicted values are consistently lower than the measured values, especially when the cylinder acts as thermosyphon. For this case, the very top of the thermosyphon is hot and drives some conduction heat transfer through the top end caps and tubing. This mode of heat transfer is not accounted for in the Zhukauskas correlation.

Figure 5 displays a plot of the surface temperature measured at each thermocouple location along the length of the condenser section of the thermosyphon at an evaporator temperature of 149 °C. Three fill volumes were chosen to represent each region of performance: 9.4% fill volume for Region I, 42.2% fill volume for Region II, and 65.6% fill volume for Region III. Region I has a nonisothermal temperature distribution that would be expected when heat transfer is governed by conduction and convection as opposed to the phase change action governing thermosyphon behavior. The surface temperature distributions are approximately isothermal for Regions II and III, though Region III has a higher average surface temperature than Region II, which is consistent

with the increased rate of heat transfer observed for an evaporator temperature of 149 °C as seen in Fig. 4.

4 Conclusions

In this paper, the effect of fill volume on the heat transfer performance, i.e., the rate of heat transfer, of a cylindrical thermosyphon with a small aspect ratio (ratio of the length of the evaporator section to the inner diameter) of 2.33 immersed in a cooling air flow is investigated. The fill volume was varied from 0% to 70.3% in a cylindrical copper-water thermosyphon having an inner diameter of 19 mm. The thermosyphon rate of heat transfer was measured as a function of evaporator temperature and fill volume in a cooling air flow (44.7 m/s at a constant ambient temperature of 23 °C). The experimental results demonstrate three distinct regions of performance. The rate of heat transfer in Region I (from 0% to roughly 16% fill volume) is largely insensitive to fill volume and evaporator temperature and was very low, which may be attributed to dry out. Regions II (extends up to roughly 58% fill volume) and III (covers the final range up to 70.3%) are both characterized by an approximate linear increase of rate of heat transfer with fill volume. For the two lower evaporator temperatures, 121 °C and 135 °C, the rate of heat transfer increases at the same rate through both of these regions. The rate of heat transfer for the two higher evaporator temperatures, however, increases more rapidly with fill volume in Region III than in Region II. The rate of heat transfer is greatest at the 70.3% fill volume at all four evaporator temperatures.

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